# a point of view on dE/dx

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INFN

October 8, 2020

# Disclamer

- This is my own point of view
- I will not make a walk across many experiments, but try to outline some general considerations and the key difficulties
- My arbitrary choices have no meaning about the merits of detectors I do not mention
- I have limited the presentation to the *classical* cases, leaving aside TPCs for very low energy, fully contained tracks and electroluminescence - which are worth a presentation on their own.
- I will try and answer to one of the questions triggered by Alan's presentation.

For the purpose of what follows, I spare you (and myself) the typing of the complete Bethe-Block and PAI(R) models formulas, and go straight to the essential.

As usual in *sampling*
$\sigma^2 \sim \sigma_0^2 + \sigma_{stat}^2$

The motivation for the *truncated mean* approach is that we know, empirically, that for a certain interval of the cutoff parameter $0.35 < \eta < 0.75$ the quantity $\langle S \rangle_\eta = \frac{1}{n} \sum_1^n S_j$

is approximately distributed as a Gaussian, so that we can write
$\sigma_{stat} \sim \frac{1}{\sqrt{n}}$.

In practical terms, taking into account also the sample length (in *cm bar*)
$\sigma \sim n^{-0.46} (xP)^{-0.32}$

Let's skip for the moment possible reasons why the second term has not been much regarded, with the exception of the very first time.

# The beginning: ISIS

W. W. M. ALLISON et al.

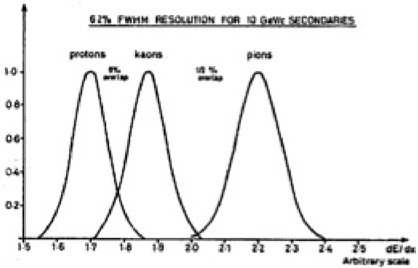


Fig. 13. The separation expected with a 5 m deep ISIS device at 10 GeV/c.

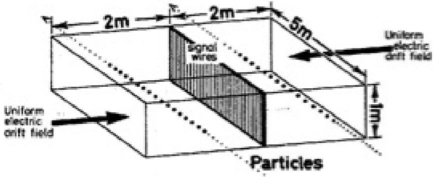


Fig. 14. The geometry of an ISIS behind an RCT.

Almost everything was already said: *Unfortunately, fluctuations in individual energy-loss measurement are very large. [...] Only by measuring many samples on each track may the required resolution of a few percent be achieved. In fact, considerably more than 100 samples [...] are required.*

The main experimental obstacles were already identified: diffusion, attenuation (i.e. attachment) and statistics.

# … but wait …

Statistics is not simply a matter of $n$. It is also meaningful what your sampling is in terms of *thickness*.

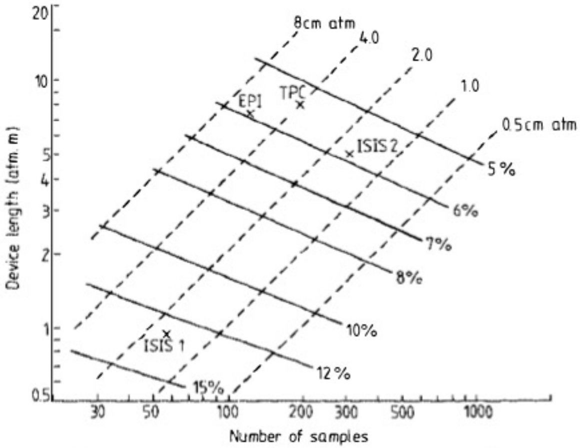


*Figure 13* The ionization resolution (% FWHM) of a multisampling detector filled with pure argon calculated with the PAI model for $\beta\gamma = 100$. The dashed lines are loci of constant sample thickness. The devices EPI, ISIS1, ISIS2, and TPC are described in Table 2.

You may play on the chessboard and place your own existing or daydreaming TPC, and see how high you score. The board is nowadays blackened with points, but the one ahead is still there.

*TPC* here was … well … the only existing one. Only much later we had to specify *PEP-4*. The hunt is still on.

# a historical perspective

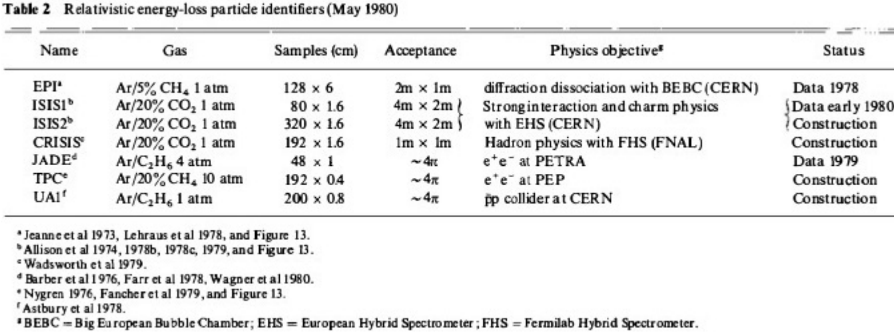


**Table 2** Relativistic energy-loss particle identifiers (May 1980)

| Name | Gas | Samples (cm) | Acceptance | Physics objective[g] | Status |
|---|---|---|---|---|---|
| EPI[a] | Ar/5% $CH_4$ 1 atm | 128 × 6 | 2m × 1m | diffraction dissociation with BEBC (CERN) | Data 1978 |
| ISIS1[b] | Ar/20% $CO_2$ 1 atm | 80 × 1.6 | 4m × 2m | Strong interaction and charm physics | Data early 1980 |
| ISIS2[b] | Ar/20% $CO_2$ 1 atm | 320 × 1.6 | 4m × 2m | with EHS (CERN) | Construction |
| CRISIS[c] | Ar/20% $CO_2$ 1 atm | 192 × 1.6 | 1m × 1m | Hadron physics with FHS (FNAL) | Construction |
| JADE[d] | Ar/$C_2H_6$ 4 atm | 48 × 1 | $\sim 4\pi$ | $e^+e^-$ at PETRA | Data 1979 |
| TPC[e] | Ar/20% $CH_4$ 10 atm | 192 × 0.4 | $\sim 4\pi$ | $e^+e^-$ at PEP | Construction |
| UA1[f] | Ar/$C_2H_6$ 1 atm | 200 × 0.8 | $\sim 4\pi$ | $\bar{p}p$ collider at CERN | Construction |

[a] Jeanne et al 1973, Lehraus et al 1978, and Figure 13.
[b] Allison et al 1974, 1978b, 1978c, 1979, and Figure 13.
[c] Wadsworth et al 1979.
[d] Barber et al 1976, Farr et al 1978, Wagner et al 1980.
[e] Nygren 1976, Fancher et al 1979, and Figure 13.
[f] Astbury et al 1978.
[g] BEBC = Big European Bubble Chamber; EHS = European Hybrid Spectrometer; FHS = Fermilab Hybrid Spectrometer.

Curiously, in Allison's 1982 paper, one can read: *ISIS is a pictorial drift chamber similar to the more recent TPC [...] Its (ISIS) prime role is particle identification; tracking is a free but impressive by-product*. This is where TPCs make a big leap: dE/dx becomes inextricably linked to tracking, in a device defining a set of (almost) independent *voxels* in a volume of gas.

... and this is why Diego's task to me was difficult: talk about dE/dx without stepping on dP/p ☺

Anyway, I cannot invent a better summary than the following table from the BRR (Blum/Riegler/Rolandi ©) bible

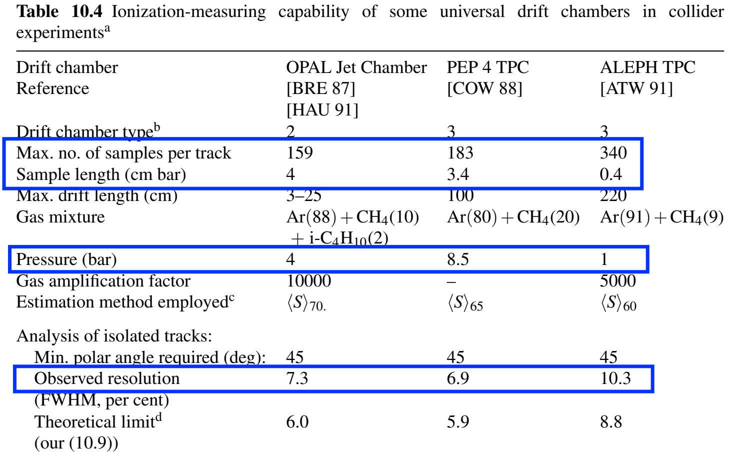


**Table 10.4** Ionization-measuring capability of some universal drift chambers in collider experiments[a]

| Drift chamber | OPAL Jet Chamber | PEP 4 TPC | ALEPH TPC |
|---|---|---|---|
| Reference | [BRE 87]<br>[HAU 91] | [COW 88] | [ATW 91] |
| Drift chamber type[b] | 2 | 3 | 3 |
| Max. no. of samples per track | 159 | 183 | 340 |
| Sample length (cm bar) | 4 | 3.4 | 0.4 |
| Max. drift length (cm) | 3–25 | 100 | 220 |
| Gas mixture | $Ar(88) + CH_4(10) + i\text{-}C_4H_{10}(2)$ | $Ar(80) + CH_4(20)$ | $Ar(91) + CH_4(9)$ |
| Pressure (bar) | 4 | 8.5 | 1 |
| Gas amplification factor | 10000 | – | 5000 |
| Estimation method employed[c] | $\langle S \rangle_{70.}$ | $\langle S \rangle_{65}$ | $\langle S \rangle_{60}$ |
| Analysis of isolated tracks: | | | |
| Min. polar angle required (deg): | 45 | 45 | 45 |
| Observed resolution (FWHM, per cent) | 7.3 | 6.9 | 10.3 |
| Theoretical limit[d] (our (10.9)) | 6.0 | 5.9 | 8.8 |

Being asked to talk about dE/dx and not dP/P made me think of NA49. This one falls in a different category than the PEP-4 TPC. In my mind, the categories are as follows

Cat 1 - *Hot* gasses

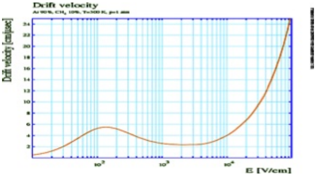
$V_{drift} \not\propto E$

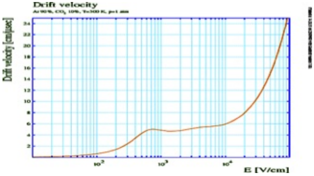
$\sigma_T \propto \frac{1}{1+(\omega\tau)^2}$

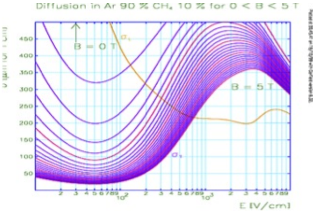
Cat 2 - *Cold* gasses

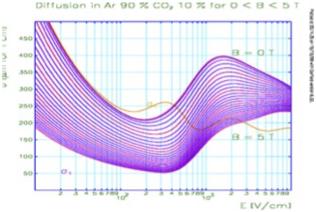
$V_{drift} \propto E$

$\sigma_T \propto \frac{1}{\sqrt{E}}$

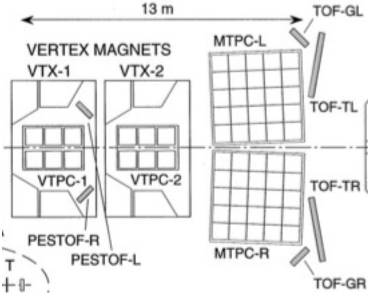








NA49 operates 4 TPCs: 2 *vertex* (VTPC) in the magnets, and 2 *main* (MTPC) ones outside.



- The MTPCs can do tracking and dE/dx, but no P measurement
- Specialized for particle ID
- They add necessary *number of samples* along the track to reach the required resolution
- The function is similar to ISIS2

Being at B=0, NA49 MTPCs are forced to be in Cat 2, with a number of consequences.

- A *cold* gas has slower drift and, in general, larger attachment
- The track density imposes a small PRF and
- Amplification in this kind of gasses tends to be lower and therefore
- Signal amplitudes are critical
- Not on a plateau of $V_{drift}$ so the calibration is more delicate

In this case exploiting the second term $(xP)^{-0.32}$ was not obvious

- HP would have slowed down the drift with potentially larger attachment (negating some of the advantages)
- would have required a sturdy field-cage, contrary to the goal of an almost transparent (literally) wall

Overall, NA49 MPTCs where in one of the most difficult corner of the TPC *phase space*.

It is the reason why I consider it a reference in this *Cat 2*, as much as the PEP-4 TPC is in *Cat 1*. Somehow, the first instance of both categories got everything right. Quite remarkable.

# traps and difficulties

- optimization of the S/N.
  - event topology and PRF
  - gas choice
  - pressure, diffusion and attachment
  - amplification
  - electronics and cross-talk
- Calibration
  - purity and stability
  - specific measurements
- Statistics
  - pad size (cm bar)
  - size of the chamber (how many samples)

It is a long list of inter-related items. Gas choice influences diffusion, attachment and amplification, which in turn are related to PRF, which is determined by the event topology and drives and actual S/N of the signals on pads, ...

An often overlooked detail is the amplification. Electronics undershoot/overshoot phenomena, maybe added on top of channel-to-channel cross-talk, can seriously disrupt S/N in certain conditions or hit configurations.

A good protective measure is allow for a large gain, which unfortunately sometimes goes against the natural propensity of protecting the gas amplifiers (wires, MPGDs, ...) by keeping the HV as low as possible.

# Calibration

NA49 has an extensive system of control, monitoring and calibration

- Gas purity is very well controlled, down to 2-4 ppm oxygen. Gas mixing has to be stabilized to very high accuracy.
- The gas system is equipped with $V_{drift}$ monitors, and gain monitors both on the input and exhaust lines. Gain is controlled to better than 0.5%, $V_{drift}$ down to $5 \cdot 10^{-4}$
- Simultaneous calibration of electronics and gas gain can be achieved by releasing a known number of electrons into the TPC drift space ($^{83}Kr$)
- Complicated corrections of electronics cross-talk at high charge density
- Charge needs to be corrected for local track angle
- Correct for charge loss due to drift length, $\leq 2\%$ due to diffusion, plus effects due to zero-suppression thresholds (apparent charge loss $\sim 5\%$)

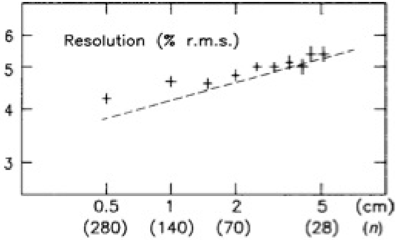
The longest tracks traverse all TPCs, both VTX and MTPC. The truncated mean is computed on the base of $(\langle S \rangle_{50})$.

Despite all the obstacles, the reported performance is $\sigma \sim \frac{38\%}{\sqrt{N}}$, giving $\sim 3\%(RMS)$ for the longest tracks, reaching identification abilities at the level of the best ones.

# One last (almost hidden) detail

In addition to the overall dimensions ($L$) and number of pads ($n$), one can play with the pad size ($x$) - or more precisely: the sample length (at a give pressure). The gain with $n$ is partly offset by the loss due to smaller $x$, but calculations seem to indicate that there is still a net gain with $n$ while keeping $L$ fixed. This seems to be supported by the following plot from ALEPH.

**Fig. 10.7** Ionization resolution at constant track length as a function of the sample length. *Crosses*: measured in the ALEPH-TPC (average track length 140 cm, argon (91%) + methane (9%) at 1 bar, diffusion < 1.4 mm r.m.s.). *Line*: prediction of Allison and Cobb, our (10.9)



A pitch much smaller than 0.4 cm is not easy, but maybe the tiny PRF of MPGD amplification and the advances in multiplexed readout will allow to exploit this possibility.

# Why not $(xP)^{-0.32}$

It is obvious that the HP path has been abandoned immediately. I can see a number of reasons. It is difficult to pin down a single reason.

- HP field cages are more difficult and expensive
- Not suitable where lightness is needed
  - because of low energy secondaries and you need additional detectors downstream
  - because you have an inner tracker in front (and Si trackers are ubiquitous)
- low- or no-hazard gas mixtures are now mandatory

The use of TPCs as gas target is reviving the issue, propelled by the use in neutrino beams.

# Summing up

- Excellent PID by dE/dx in TPCs is well established since the beginning, with yet to be surpassed performance
- In this game, anything impacting the overall S/N is critical, and ...
- Detailed calibration is paramount
- Number of samples, and/or effective sampling [cm bar] is still the key factor, so whenever possible ... eat up all the available volume (or go HP) and keep your allocated volume in one single piece (do not slice it!)
- I am not sure we will see very soon a TPC with 500 $1mm$ samples, but I'm curious to see what would happen.
- An *enabling technology* for the future of HP is the field-cage construction, where I have the feeling much can be done with modern techniques.